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Application of Adomian Decomposition Method to Nonlinear Heat Transfer Equation

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Abstract

The Adomian Decomposition Method is employed in the solution of the unsteady convective radiative equation. The Adomian Decomposition Method is provided an analytical solution in the form of an infinite power series. The comparison of the results obtained by ADM and VIM The effect of Adomian polynomials terms is considered on accuracy of the results. The temperature profiles in fin are obtained. Results show a good accuracy. The Adomian decomposition method (ADM) is used in obtaining more meaningful and valid solutions.

Keywords: Adomian decomposition method, Heat transfer, Radiation equation

1. Introduction

Most of scientific problems and phenomena especially in mechanical engineering occur nonlinearly. Heat transfer equations in straight surfaces, are one most applicable of them. One of these surfaces is straight fins that are employed to enhance the heat transfer between the primary surface and its convective, radiating or convective-radiating environment. Extended surfaces are extensively used in various industrial applications [1]. Aziz and Hug [2] used the regular perturbation method to obtain a closed form solution for a straight convecting fin with temperature dependent thermal conductivity. A method of temperature correlated profiles is used to obtain the solution of optimum convective fin when the thermal conductivity and heat transfer coefficient are functions of temperature [3].Yu and Chen [4] assumed that the linear variation of the thermal conductivity and exponential function with the distance of the heat transfer coefficient and then, solved the nonlinear conducting-convecting-radiating heat transfer equation by the differential transformation method. Bouaziz et al. [5] presented the efficiency of longitudinal fins with temperature-dependent thermo-physical properties.

Many different methods have recently introduced to solve nonlinear problems, such as the homotopy analysis method [6], the variational iteration method (VIM) [7–11,12], the Adomian's decomposition method (ADM) [13,14] , homotopy analysis method [15, 16], and homotopy perturbation method [17–19,20-23].Recently, the Adomian Decomposition Method (ADM) was used to solve a wide range of physical problems. This method provides a direct scheme for solving linear and nonlinear deterministic and stochastic equations without the need for linearization and yields convergent series solutions rapidly [24].

An advantage of this method is that, it can provide analytical or an approximated solution to a rather wide class of nonlinear (and stochastic) equations without linearization, perturbation, closure approximation, or discretization methods. Unlike the common methods which are only applicable to systems with weak nonlinearity and small perturbation and may change the physics of the problem due to simplification, AD Mgives the approximated solution of the problem without any simplification. Thus, its results are more realistic [25]. During recent years, several researchers have tried to modify the ADM.

Wazwaz [26] developed a fast and accurate algorithm for solution of sixth-order boundary value problems. Jafari and Daftardar-Gejji [27] modified ADM to solve a system of nonlinear equations. They obtained a series solution with faster accelerated convergence than the series obtained by the standard ADM. Luo [28] revised ADM for cases involving inhomogeneous boundary conditions, using a suitable transformation. Luo [29] proposed an efficient modification to ADM, namely two-step Adomian Decomposition Method (TSADM) that facilitated the calculations. Zhang [30] presented a modified ADM to solve a class of nonlinear singular boundary value problems, which arise as nonlinear normal model equations in nonlinear conservative vibratory systems. Zhu et al.[31] presented a new algorithm using parameterization for calculating Adomian polynomials for nonlinear operators. Abbasbandy [32] presented some efficient numerical algorithms to solve a system of two nonlinear equations (with two variables) based on Newton's method. Biazar et al. [33] extended the solution of ordinary differential equations by ADM. Daftardar-Gejji and Jafari [34] presented an iterative method for solving nonlinear functional equations. Now, several researchers have used the ADM to solve a wide range of physical problems in various engineering fields such as vibration and wave equation [35], porous media simulation [36], and other nonlinear systems.

In this Letter, the mathematical model of Adomian decomposition method is introduced and then its application in heat transfer equations is studied.

2. Formulation of Adomian Decomposition Method

Consider equation $Fu(t) = g(t)$, where F represents a general nonlinear ordinary or partial differential operator including both linear and nonlinear terms. The linear terms are decomposed into $+ R$, where L is easily invertible (usually the highest order derivative) and R R is the remains of the linear operator. Thus, the equation can be written as [3]

$$Lu + Ru + Nu = g \tag{1}$$

Where, Nu indicates the nonlinear terms. By solving this equation for Lu, since L is invertible, we can write

$$L^{-1}Lu = L^{-1}g - L^{-1}Ru - L^{-1}Nu \tag{2}$$

If L is a second-order operator, L^{-1} is a two fold indefinite integral, by solving Eq. (2) for u, we get

$$u = A + Bt + L^{-1}(g) + L^{-1}Ru - L^{-1}Nu \tag{3}$$

where A and B are constants of integration and can be found from the boundary or initial conditions. Adomian method assumes the solution u can be expanded into infinite series as

$$u = \sum_{n=0}^{\infty} u_n \tag{4}$$

Nomenclature

A area . . . . (m2)

C specific heat . . . . (J/kg K)

Ca specific heat at temperature Ta . . . . (J/kg K)

Eg surface emissivity . . . .(W)

h coefficient of natural convection . . . . . . (W/m2K)

VIM variational iteration method

k thermal conductivity . . . . (W/mK)

ka thermal conductivity in $T = Ta$ . . . . (W/mK)

L latent heat length . . . . (m)

T temperature . . . . (K)

Ta environment temperature . . . . (K)

Ts effective sink temperature . . . .(K)

Tb temperature at the base . . . . (K)

Ti initial temperature . . . . (K)

V volume . . . . (m3)

Q heat-transfer rate . . . . (W)

α thermal diffusivity . . . . (m2/s)

β constant, volumetric thermal expansion coefficient . . . . (1/K)

ε small parameter . . . .(–)

ρ density . . . . (kg/m3)

σ Stefan–Boltzman constant . . . . (–)

η fin efficiency

Subscripts

a air

g surface emissivity

S surface

b base temperature

also, the nonlinear term Nu will be written as

$$Nu = \sum_{n=0}^{\infty} A_n \tag{5}$$

where A_n are the special Adomian polynomials. By substituting Eqs. (4) and (5) in Eq. (3), the solution can be written as

$$\sum_{n=0}^{\infty} u_n = u_0 - L^{-1}R\sum_{n=0}^{\infty} u_n - L^{-1}\sum_{n=0}^{\infty} A_n \tag{6}$$

where u_0 is identified as: $A + Bt + L^{-1}(g)$ [3].

In Eq. (6), the Adomian polynomials can be generated by several means. Here we used the following recursive formulation:

$$A_n = \frac{1}{n}\left[\frac{dn}{d\lambda^n}\left[N\left(\sum_{n=0}^{\infty}\lambda^i u_i\right)\right]\right]_{\lambda=0} \quad \text{, n=0, 1, 2, 3,...} \tag{7}$$

Since the method does not resort to linearization or assumption of weak nonlinearity, the solution is generated in the form of general solution and it is more realistic compared to the method of simplifying the physical problems.

3. Problem description

The example to be studied is the one-dimensional heat transfer in a straight fin with the length of *L* and the cross section area of *A* and the perimeter of *P* (see Fig. 1). The fin surface transfers heat through both convection and radiation. Suppose the temperature of the surrounding air is T_0 and the effective sink temperature for the radiative heat transfer is T_s . We assume that base temperature of the fin is T_b and there is no heat transfer of the tip of the fin. It is also assumed that the convection heat transfer coefficient, *h*, and the emissivity coefficient of surface, E_g, are both constant while conduction coefficient, *k*, can be variable. The energy equation and the boundary conditions for the fin are as follows:

$$\frac{d}{dx}\left(k\frac{dT}{dx}\right) - \frac{hp}{A}(T - T_a) - \frac{E_g\sigma}{A}(T^4 - T_s^4) = 0 \tag{8}$$

$$x = 0 \rightarrow \frac{dT}{dx} = 0, \quad x = L \rightarrow T = T_b \tag{9}$$

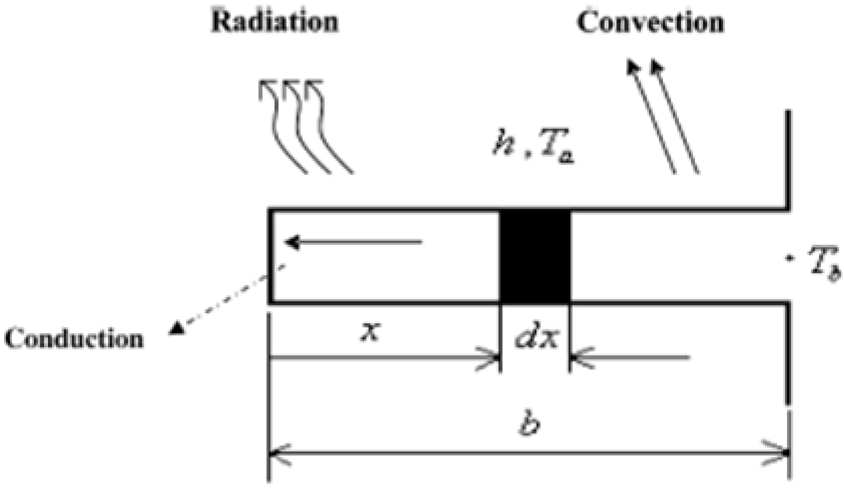

Fig.1. Geometry of a strait fin

Assuming k as a linear function of temperature, we have:

$$k = k_a(1+\beta(T-T_a)) \tag{10}$$

After making the equation dimensionless and changing parameters, we have:

$$\theta = \frac{T}{T_b} \;,\; \theta_a = \frac{T_a}{T_b} \;,\; \theta_s = \frac{T_s}{T_b} \;,\; X = \frac{x}{L} \;,\; N^2 = \frac{hpL^2}{k_a A} \;,\; \varepsilon_1 = \beta T_B \tag{11}$$
$$\varepsilon_2 = \frac{Eg\delta T_b{}^2 pL^2}{k_a A}$$

And substituting Eq. (11) in Eq. (8) we have:

$$\frac{d}{dx}\left\{\left[1+\varepsilon_1(\theta-\theta_a)\right]\frac{d\theta}{dx}\right\} - N^2(\theta-\theta_a) - \varepsilon_2(\theta^4-\theta_s{}^4) = 0 \tag{12}$$

$$x = 1 \rightarrow \theta = 1 \qquad x = 0 \rightarrow \frac{d\theta}{dx} = 0, \tag{13}$$

by assuming $\theta_a = \theta_s = 0$ we have :

$$\frac{d^2\theta}{dX^2} - N^2\theta + \varepsilon_1\left(\left(\frac{d\theta}{dX}\right)^2 + \theta\frac{d^2\theta}{dX^2}\right) - \varepsilon_2\theta^4 \tag{14}$$

4. Problem Solution:

To apply ADM on the wedge Eq. 14 in operator form as

$$L\theta = N^2\theta - \varepsilon_1((\frac{d\theta}{dX})^2 + \theta\frac{d^2\theta}{dX^2}) + \varepsilon_2\theta^4 \tag{15}$$

where the differential operator L is given by $L = \frac{d^2}{dx^2}$ and assume the inverse of the operator L exists and it can be integrated from 0 to X i.e. $L^{-1} = \int_0^x\int_0^x (.)dXdX$ .Operating with L^{-1} on 15, yields $L^{-1}L\theta = L^{-1}(N^2\theta - \varepsilon_1((\frac{d\theta}{dX})^2 + \theta\frac{d^2\theta}{dX^2}) + \varepsilon_2\theta^4)$. Then, we have:

$$\theta(x) = \theta(0) + \theta'(0)X + L^{-1}(N^2\theta - \varepsilon_1((\frac{d\theta}{dX})^2 + \theta\frac{d^2\theta}{dX^2}) + \varepsilon_2\theta^4) . \tag{16}$$

From the boundary conditions of (13) and taking $\theta(0) = a$ ADM solution can be obtained by:

$$\theta(x) = a + L^{-1}(N^2\theta - \varepsilon_1((\frac{d\theta}{dX})^2 + \theta\frac{d^2\theta}{dX^2}) + \varepsilon_2\theta^4) \tag{17}$$

ADM is introduced in the following expression:

$$\theta(X) = \sum_0^\infty \theta_n(X) \tag{18}$$

The ADM is defined as the nonlinear function $N(\theta(x))$ by an infinite series of polynomials

$$N(\theta(x)) = -\varepsilon_1((\frac{d\theta}{dX})^2 + \theta\frac{d^2\theta}{dX^2}) + \varepsilon_2\theta^4) \tag{19}$$

Adomian polynomials A_n represent the nonlinear term $N(\theta(x))$ and can be calculated from (7). The ADM is defined as the linear function $R(\theta(x))$ by an infinite series of polynomials. Adomian polynomials R_n represent the linear term $R(\theta(x))$ and can be calculated from

$$R(\theta(x)) = N^2\theta \tag{20}$$

Substituting (18) and (19) and (20) into (17) yields

$$\sum_{n=0}^\infty \theta_n(x) = a + L^{-1}\sum_{n=0}^\infty R_n + L^{-1}\sum_{n=0}^\infty A_n \tag{21}$$

To determine the components of A_n and θ_n , θ_0 was defined from the boundary condition of (13)

$$\theta_0(x) = a \tag{22}$$

For determination of the other components of $\theta(x)$, we have

$$\theta_{n+1}(x) = L^{-1}R_n + L^{-1}A_n \qquad \text{n=1,2,…} \tag{23}$$

By using (7) and, we obtain the following few terms of Adomian polynomials A_n :

$$A_0 = -\varepsilon_1((\frac{d\theta_0}{dX})^2 + \theta_0 \frac{d^2\theta_0}{dX^2})) + \varepsilon_2\theta_0^4$$

$$A_1 = -\varepsilon_1(\theta_1(\frac{d^2\theta_0}{d^2X}) + \theta_0(\frac{d^2\theta_1}{dX^2}) + 2(\frac{d\theta_0}{dX})(\frac{d\theta_1}{dX})) + 4\varepsilon_2\theta_0^2\theta_1$$

$$A_2 = -\varepsilon_1(\frac{1}{2})(2\theta_2(\frac{d^2\theta_0}{dX^2}) + 2\theta_1(\frac{d^2\theta_1}{dX^2}) + 2\theta_0(\frac{d^2\theta_2}{dX^2}) + 2(\frac{d\theta_1}{dX})^2 + 4(\frac{d\theta_0}{dX})(\frac{d\theta_2}{dX})) + 6\varepsilon_2\theta_1^2\theta_0^2$$
$$+ 4\varepsilon_2{\theta_0}^2\theta_2$$

$$A_3 = -\varepsilon_1(\frac{1}{6})(6\theta_3(\frac{d^2\theta_0}{dX^2}) + 6\theta_2(\frac{d^2\theta_1}{dX^2}) + 6\theta_1(\frac{d^2\theta_2}{dX^2}) + 6\theta_0(\frac{d^2\theta_2}{dX^2}) + 12(\frac{d\theta_1}{dX})(\frac{d\theta_2}{dX}) + 12(\frac{d\theta_0}{dX})$$
$$(\frac{d\theta_3}{dX})) + 4\varepsilon_2\theta_1^3\theta_0 + 12\varepsilon_2{\theta_0}^2\theta_1\theta_2 + 4\varepsilon_2\theta_3\theta_0^3$$

And of (23), for determining of $\theta(X)$, we have

$$\theta_0 = a$$

$$\theta_1 = \frac{1}{2}N^2aX^2 + \frac{1}{2}\varepsilon_2a^4X^2 \tag{24}$$

$$\theta_2 = \frac{1}{4}N^2(\frac{1}{6}N^2a + \frac{1}{6}\varepsilon_2a^4)X^4 + \frac{1}{3}\varepsilon_2a^3(\frac{1}{2}N^2a + \frac{1}{2}\varepsilon_2a^4)X^4 - \frac{1}{2}\varepsilon_1a(N^2a + \varepsilon_2a^4)X^2$$

$$\theta_3 = N^2(\frac{1}{6}(\frac{1}{20}N^2(\frac{1}{6}N^2a + \frac{1}{6}\varepsilon_2a^4) + \frac{1}{15}\varepsilon_2a^3(\frac{1}{2}N^2a + \frac{1}{2}\varepsilon_2a^4))X^6 - \frac{1}{24}\varepsilon_1a(N^2a +$$
$$\varepsilon_2a^4)X^4) + \frac{1}{6}(\frac{6}{5}\varepsilon_2a^2(\frac{1}{2}N^2a + \frac{1}{2}\varepsilon_2a^4)^2 + \frac{4}{5}\varepsilon_2a^3(\frac{1}{4}N^2(\frac{1}{6}N^2a + \frac{1}{6}\varepsilon^2a^4) + \frac{1}{3}\varepsilon_2a^3(\frac{1}{2}$$
$$N^2a + \frac{1}{2}\varepsilon_2a^4)))X^6 + \frac{1}{4}(-\frac{1}{6}\varepsilon_1(2(\frac{1}{2}N^2a + \frac{1}{2}\varepsilon_2a^4)(N^2a + \frac{1}{2}\varepsilon_2a^4) + 2a(3N^2(\frac{1}{6}N^2a$$
$$+ \frac{1}{6}\varepsilon_2a^4) + 4\varepsilon_2a^3(\frac{1}{2}N^2a + \frac{1}{2}\varepsilon_2a^4)) + 2(N^2a + \varepsilon_2a^a))X^4 + \frac{1}{2}\varepsilon_1^2a^2(N^2a + \varepsilon^2a^4)X^2$$

... .

We use

$$\theta = \sum_{n=0}^{\infty} \theta_n = \theta_0 + \theta_1 + \theta_2 + \theta_3 + ... \quad (25)$$

According to Eq. (25), the accuracy of ADM solution increases by increasing the number of solution terms (n).For the complete solution of Eq. (25), a should be determined. From the boundary conditions of (13) and taking $\theta(1) = 1$ and by substituting Eq (25) a can be obtained:
a = 0.6687006641

5-Results and discussion

Fig. 2 shows the temperature distribution in convective–radiative conduction fins with variable thermal conductivity at $\varepsilon_2 = .2$ and $N = 1$. Fig. 3 shows the temperature distribution in convective–radiative conduction fins with variable fin dimension at $\varepsilon_2 = .2$ and $N = 1$ .According to eq (11) this dimension are L ,A and P .Fig. 4 shows temperature distribution in convective–radiative conduction fins with variable parameter N.

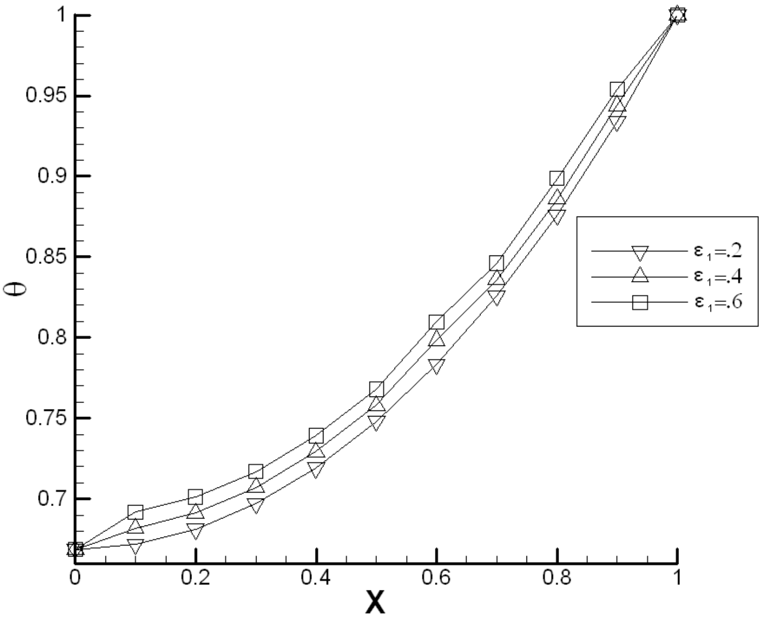

Fig.2. Temperature distribution in convective–radiative conduction finswithvariablethermal conductivity for $\varepsilon_2 = .2$, $N = 1$

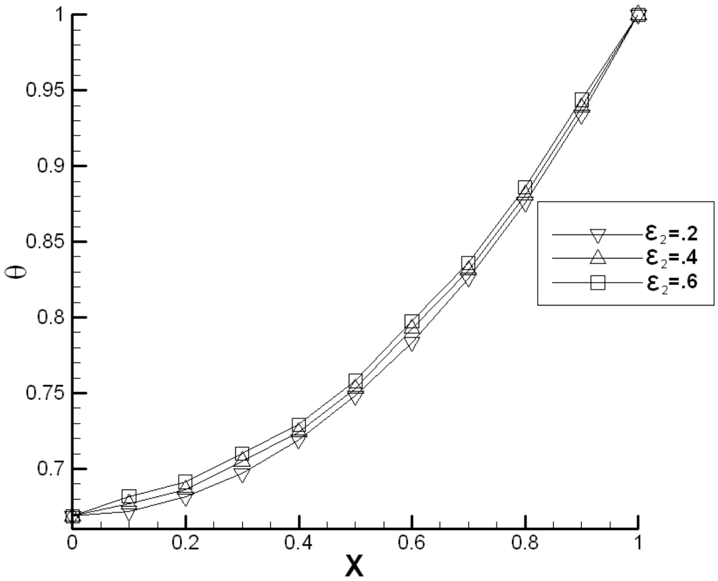

Fig.3. Temperature distribution in convective–radiative conduction fins with variable fin dimension for $\varepsilon_1 = .2$, $N = 1$

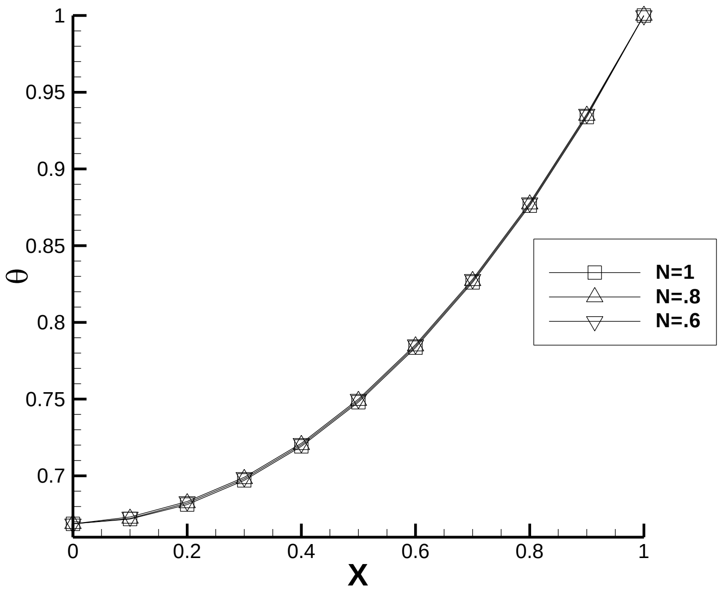

Fig. 4 Temperature distribution in convective–radiative conduction fins with variable parameter N.

We show in fig 4 the comparison of the results obtained by ADM and VIM [37], for the $\varepsilon_1 = .2, \varepsilon_2 = .2$, $N = 1$ and in fig 5 the comparison of the results obtained by ADM and HAM [38], for the $\varepsilon_1 = .2, \varepsilon_2 = .2$, $N = 1$. There are a few differences between the ADM and VIM solution because the ADM provides an analytical solution in terms of an infinite power series. There is not difference between the ADM and HAM solution because these methods are very similar.

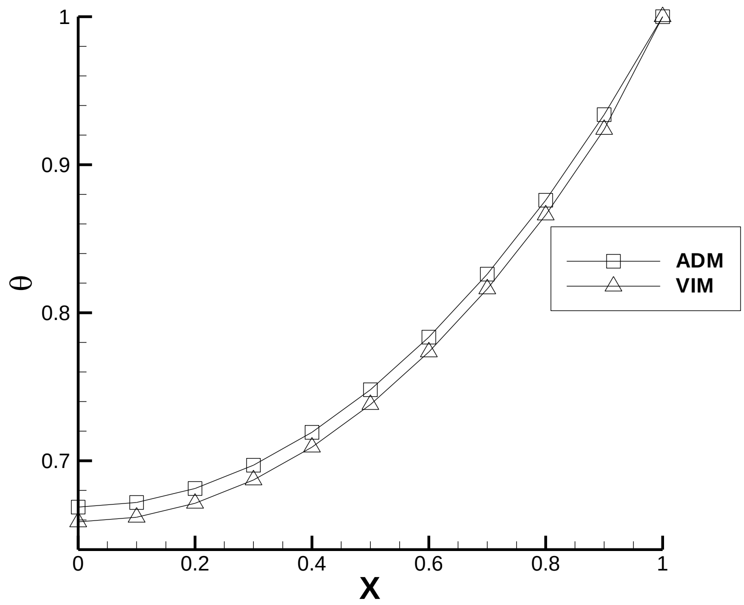

Fig 5. The comparison of the results obtained by ADM and VIM [37], at $\varepsilon_2 = .2$, $\varepsilon_1 = .2$ **and** $N = 1$

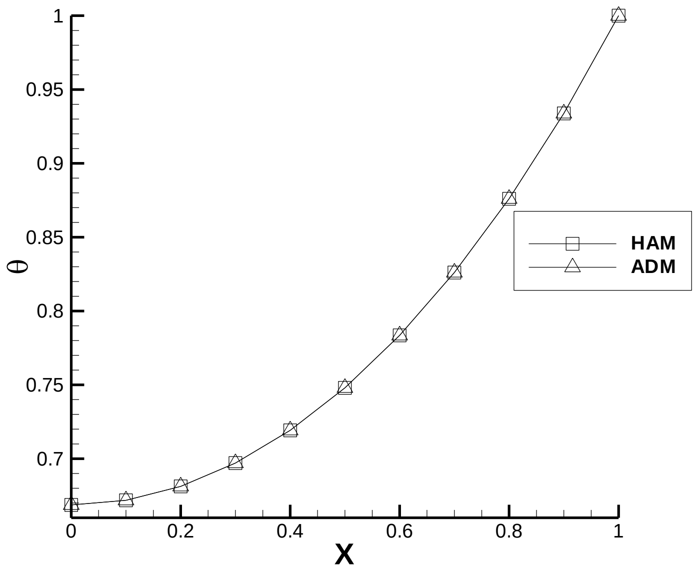

Fig 6. The comparison of the results obtained by ADM and HAM [38], at $\varepsilon_2 = .2$, $\varepsilon_1 = .2$ **and** $N = 1$

6. Conclusions

In this Letter the Adomian decomposition method has been successfully implemented to find the solution of nonlinear heat transfer equations. The results are shown graphically. The

Adomian decomposition method (ADM) can provide analytical approximation or approximated solution to a rather wide class of nonlinear (and stochastic) equations without linearization, perturbation, closure approximation, or discretization methods. The effect of Adomian polynomial terms is considered and shows that the accuracy of results is increased with the increasing of Adomian polynomial terms.

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